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An integrated haptic-enabled virtual reality system for orthognathic surgery planning

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Abstract

Conventional Orthognathic surgery (OGS) planning involves cephalometric analyses and dental casts to be mounted on an articulator; where dental segments are identified, cut and repositioned; allowing the fabrication of intraoral wafers to guide the positioning of the osteotomy bone segments. This conventional planning introduces many inaccuracies that affect the post-surgery outcomes. The advances in computer technologies have allowed the development of computational tools for OGS planning. However, these tools have failed in providing a practical solution because they have focused on some specific stages of the planning process, and their ability to transfer preoperative planning data to the operating room is limited. This paper proposes a new integrated haptic-enabled virtual reality system for OGS planning. The system incorporates virtual reality (VR) and haptics through the planning process, being able to generate preoperative planning data. Virtual diagnosis and planning aided tools are also incorporated into the virtual environment. After the development and implementation of the proposed system, a functionality evaluation was carried out. The results demonstrated that the proposed

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virtual OGS planning method is feasible and more effective than the traditional approach at increasing the intuitiveness and reducing errors and planning times.

Keywords: orthognathic surgery (OGS); virtual reality (VR); haptic technologies; Computer-Aided surgery; surgery planning.

1. Introduction

Orthognathic surgery (OGS) is a medical procedure aiming to correct face miss-alignment and dentofacial deformities (Posnick 2013). It requires a precise pre-surgical planning to generate the surgical data needed in the operating room. The conventional OGS planning process comprises: (1) a facial study; (2) two-dimensional cephalometric analyses on a lateral radiography; (3) a model surgery procedure in which the patient's dental cast models are mounted on an articulator in order to be cut and repositioned to get the desired patient's occlusion; and (4) the fabrication of the surgical template corresponding to the desired occlusion. Although effective, this conventional planning approach is time consuming and the results depends on the accurate recording of the dental occlusion and mounting of casts on the articulator, which in some cases generates inaccuracies that affect the post-surgery results. Moreover, the preoperative planning to obtain the desired skeletal harmony is a complex and extensive process, and depicts a significant challenge for surgeons, in particular when correcting complex malformations (Proffit et al. 2006; McCormick and Drew 2011; Posnick 2013; Birbe 2014).

From the emergence of computer technologies and virtual reality (VR), several research works have focused on the development of Computer-Aided systems for medical applications. These systems have been oriented to assist specialists in medical tasks such as diagnosis, planning and simulation of different surgical procedures in a virtual environment (Neumann et al. 1999; Ruiz and Montagut 2009). Moreover, the sense of touch by means of haptic technologies has also been integrated in many of these systems

(Agus 2003; Coles et al. 2011; Lin et al. 2014; Banerjee and Luciano 2017). These later systems represent a knowledge and experience-based approach in which the surgical skills of surgeons are incorporated, allowing the training of medical students and novice practitioners. Haptics allows the tactile interaction with the patient's virtual model and enables the real-time motion of surgical instruments (Vázquez-Mata 2008; Syed 2011; Olsson et al. 2013; Medellin-Castillo et al. 2016).

In the area of OGS, the traditional planning process started to evolve with the use of computer methods to carry out 2D cephalometric analyses (Haas Jr et al. 2014). The next evolution involved the use of modern engineering and computer technologies, allowing the 3D reconstruction and visualization of the patient skull, the segmentation of the patient's virtual model, the displacement and relocation of bone fragments, and the design of the surgical guide to assist the real surgical procedure. These modern OGS planning systems integrate engineering tools such as Computer-Aided Design and Computer Aided Manufacture (CAD/CAM) for model sectioning, bone manipulation, surgical guide design and fabrication (Swennen GR et al. 2009; Swennen GRJ 2017).

Although several authors have reported that the use of Computer-Aided planning systems improves the traditional OGS planning process; these computer tools have failed in providing an integrated solution because they have been developed as separate modules, focusing on some specific stages of the planning process (Gossett et al. 2005; Kusnoto 2007; Nadjmi et al. 2010; McCormick and Drew 2011; Levine et al. 2012). As a consequence, the transfer of preoperative planning data along the planning process, and to the operation room, is a major issue in current computer-based OGS planning systems. Moreover, no haptic-enabled virtual surgical planning methods for integrated OGS planning have been proposed in the literature. (Bettega et al. 2000; Heiland et al. 2004; Gossett et al. 2005; Swennen GR et al. 2009; Levine et al. 2012).

This paper presents a novel virtual and haptic-enabled system for integrated orthognathic surgery planning. The proposed system allows the comprehensive planning of OGS by incorporating all the planning stages into a unique Computer-Aided platform. Furthermore, the proposed system is able to automatically generate the relevant surgical data needed by the specialist in the operating room.

2. Related works

2.1 Computer-Aided planning in orthognathic surgery

Orthognathic surgery is a medical procedure with the aim of correcting dento-facial deformities and facial miss-alignments. It requires an accurate pre-surgical planning to achieve surgical outcomes. Traditionally, the OGS planning process involves four steps:

(1) *Clinical facial analysis.* It is conducted on patient’s frontal and lateral face photographs. By means of the facial analysis the surgeon determines a preliminary diagnosis and treatment, i.e. an orthodontics or surgery treatment.

(2) *Cephalometric analysis.* To confirm the previous diagnosis and treatment, a cephalometric analysis is carried out on a lateral skull radiography. The cephalometric values are compared with pre-established standards to determine a final diagnosis and treatment.

(3) *Model surgery.* When a surgical procedure is needed, a model surgery procedure is then performed. The model surgery allows surgeons to correct the maxillary misalignment by using the patient’s dental cast models, which are mounted on an articulator to simulate the patient's maxillary and mandibular position. On the articulator, the dental casts are manually segmented and repositioned to achieve the desired patient’s occlusion.

(4) *Surgical template generation.* Once the desired maxillary position is obtained, the new patient's occlusion is recorded manually on an acrylic surgical template, enabling surgeons to transfer the surgical planning outcomes to the operating room.

In the last decades, the development of computer technologies and VR have allowed the evolution of the traditional OGS planning process. Several platforms for Computer-Aided cephalometry have been develop and are commercially available. In these systems different types of cephalometric analyses can be made simultaneously in a very short time. With the emergence of 3D scanning technologies such as CT and MRI, several methodologies to carry out virtual model surgery procedures have also been proposed. These methodologies includes those that consider the 3D scanning of the dental cast models to allow the model repositioning in a virtual environment (Chapuis et al. 2005; Kim et al. 2011). Other methodologies for model surgery suggest the 3D reconstruction of the patient's skull to perform the virtual segmentation and repositioning. Regarding the generation of the surgical wafer, several works have proposed the integration of engineering CAD/CAM tools (Gelesko et al. 2012; Li 2013) to enable the inclusion of advanced fabrication techniques such as additive manufacturing (AM).

A summary of the main characteristics of some existing systems for Computer-Aided OGS planning, is presented in Table 1.

Table 1. Characteristics of existing Computer-Aided systems for OGS planning.

System	Status	F.A.	C.A.	M.S.	W.G.	S. I. G.	Key features
Maxilim® (Medicim NV, Mechelen, Belgium) (MedicimNV 2008)	C	-	-	X	X	½	- 3D patient's model visualization. - Model segmentation and reposition. - Wafer generation by CAD techniques. - Report generation of maxilla repositioning.

ProPlan CMF® (Materialise, Leuven, Belgium) (Materialise 2017)	C	-	X	X	X	½	- 2D/3D patient's visualization. - 3D cephalometric analysis in base 2D projection. - Surgical wafer model generation.
Dolphin Imaging® (PathersonDentalSupply 2017)	C	-	X		-	½	- DICOM, jpg, png and tif files reader. - 2D cephalometric analysis. - Cephalometric superposition over patient photography. - 2D simulation of orthodontic and surgical treatment. - Report generation for cephalometry, and patient medical data.
NemoFab® (NemoTec, Madrid, Spain) (NemoTec 2016)	C	-	X	X	X	½	- 2D /3D patient's anatomy visualization. - 3D/ 2D cephalometric analysis. - Surgical wafer design by CAD tools.
Keeve et al. (1996) (Keeve et al. 1996)	R	-	-	X	-	½	- 3D skeletal patient's reconstruction from DICOM data. - Soft tissue reconstruction from patient's photos. - Virtual model segmentation by cutting planes.
CAVOS/Xia et al. (2000) (Xia J et al. 2000)	R	-	-	X	X	½	- 3D patient's reconstruction from DICOM data. - Virtual model segmentation and repositioning by 3D mouse. - Surgical wafer generation by CAD tools. - Report generation for maxillary repositioning.
Bettega et al. (2000) (Bettega et al. 2000)	R	-	X	X	-	-	- 3D ceph-analysis by 2D landmarks projection. - Combination of model surgery and orthodontia. - Model surgery by cast models superposition.
Chapuis et al. (2005) (Chapuis et al. 2005)	R	-	-	X	-	-	- 3D patient's reconstruction from DICOM data. - Surgery model by dental cast models scanned. - Reposition models enable.
Noguchi et al. (2007) (Noguchi et al. 2007)	R	-	X	X	-	-	- 2D lateral cephalograms reader from X-Ray. - Soft-tissue and dental cast models reconstruction from laser scanner. - Computing of virtual displacement of dental cast models.

							- 3D cephalometric analysis based on 2D cephalometry.
CASSOS/Jones et al. (2007) (Jones et al. 2007)	R	-	X	2D	-	X	- 2D lateral X-Ray reader. - Soft tissue face profile analysis. - 2D maxillary reposition from cephalograms.
Olszewski et al. (2008) (Olszewski et al. 2008)	R	-	X	X	-	-	- 3D patient's reconstruction from CT data. - 3D cephalometry from 2D projection. - Segmentation model from visual guidance recorded by camera. - Model reposition enable.
Nadjmi et al. (2010) (Nadjmi et al. 2010)	R	-	-	X	-		- Virtual model surgery from scanned dental cast models. - Segmentation process not necessary.
Olsson et al. (2013) (Olsson et al. 2013)	R	-	-	X	-		- 3D patient's reconstruction. - Collision detection between virtual models. - Stereo rendering. - Haptic force feedback enabled.
VR-MFS/Wu et al. (2013) (Wu et al. 2014)	R	-	-	X			- 3D visualization of the hard and soft tissues. - Model segmentation from a free path defined by the user. - Haptic interaction user-virtual model enabled.
Medellin et al. (2016) (Medellin-Castillo et al. 2016)	R	-	X	-	-	½ (ceph)	- 2D /3D patient's anatomy visualization. - 3D cephalometric -analysis by 2D landmarks projection and haptically aided. - Cephalometric report generation.

C: commercial, R: research, F.A.: facial analysis, C.A.: cephalometric analysis, M.S.: model surgery, W.G.: wafer generation, S.I.G.: generation of surgical information, X: available, ½: available with limitations.

From Table 1 it can be observed that most of the systems have focused on specific stages of the OGS planning process. Some systems integrate the capability to reconstruct the patient´s 3D model from CT data, and tools to carry out 2D and 3D cephalometric analyses. Some other systems integrate segmentation and repositioning tools to allow 3D model surgery and surgical wafer design. On the other hand, commercial systems are an alternative to accomplish specific stages of the traditional OGS planning process; however, they are expensive and require an extensive practice. Moreover, existing systems do not assist surgeons in tasks such as clinical diagnosis and facial analysis, and only few of them allow the spatial perception of the patient's anatomy by means of haptic technologies. Thus, the main drawbacks of existing OGS planning are:

(1) None of the systems includes the patient’s facial analysis.

(2) Computer-Assisted clinical diagnosis has not been integrated in existing OGS systems.

(3) Clinical data interchange among the different OGS planning systems is needed for a comprehensive surgical planning.

(4) Tools for segmentation and repositioning of virtual models are still required to accomplish virtual model surgery.

(5) Although several systems allow surgeons to carry out the surgical wafer design using engineering tools such as CAD/CAM, these systems require a high experience and knowledge of the design tools.

(6) The transfer of preoperative planning data to the operation room is still limited to some specific planning steps.

According to Bettega et al. (2000), the minimal functionalities needed in a OGS planning system are the capability to execute cephalometric analysis, model segmentation, and repositioning of the model segments. These three minimal functionalities can be identified in some of the OGS systems shown in Table 1. However, there are still some stages of the conventional OGS planning process that have not been integrated in these systems and that limit their practical use.

2.2 Haptics in orthognathic surgery planning

VR medical applications provide specialists the capability to plan, simulate and train several surgical procedures to increase their level of knowledge, experience and manual abilities (Agus 2003; Vázquez-Mata 2008). However, when the sense of touch is enabled in a VR environment, the level of realism, interaction, and intuitiveness also increase (Panait et al. 2009). The sense of touch is provided to the user as a force feedback generated by a haptic interface (Coles et al. 2011). Haptic technologies provide users the spatial sensation, i.e. the user can touch and feel the depth of virtual objects, which does not occur with simple PC-Mouse VR interaction.

Many surgical planning and simulation systems have demonstrated the importance of enabling the sense of touch and force feedback by means of haptic technologies (Ranta and Aviles 1999; Dangxiao et al. 2012; Xia P et al. 2012; Olsson et al. 2013; Medellin-Castillo et al. 2016). In Medellin-Castillo et al. (2016) a haptic-enabled system for 3D cephalometric analysis was presented. Haptics was integrated into the proposed system in order to identify and mark the ceph-landmarks on a 3D patient´s model, allowing users to recognise the patient´s skull characteristics that define the anatomic landmarks. According to Olsson et al. (2013), the haptic feedback gives users the capability to increase their performance by reducing the planning time and increasing the user's manual skills (Ranta and Aviles 1999; Dangxiao et al. 2012).

Thus, haptic technologies have the potential to improve the Computer-Aided surgical planning process by providing surgeons the capability to interact with the patient models in a more intuitive and realistic approach. The integration of the sense of touch and force feedback into a virtual environment for OGS planning, eases the bone sectioning and alignment, and allows users to explore anatomic features and reduce the skill learning curve for novice surgeons, (Agus 2003; Aboul-Hosn Centenero and Hernandez-Alfaro 2012; Olsson et al. 2013).

3. System description

The proposed integrated orthognathic surgery system, named as OSSys, comprises four modules as shown in Figure 1:

(1) *Facial analysis module.* Integrates tools to perform facial analyses on patient's images in order to provide surgeons with a preliminary diagnosis of the patient's anatomical pathology.

(2) *Cephalometric analysis module.* Allows the realization of Computer-Aided cephalometric analyses and diagnosis. Various cephalometric methodologies have been implemented in this module.

(3) *Model surgery module.* Comprises assisting tools to carry out model surgery procedures on 3D models of patients' skulls.

(4) *Surgical template module.* Includes Computer-Aided design tools to generate semi-automatically the surgical wafer needed to guide the bone segment repositioning during the real surgical procedure.

These four main modules interact with each other by means of the following integrating modules:

- *Graphics module.* Responsible of creating the virtual scene and rendering the virtual patient's models.
- *Input/output data module.* Responsible of collecting, computing and logging all the preoperative planning data, including the surgical information needed in the operating room and the surgical wafer.
- *Haptic-physics module.* Responsible of the dynamic behaviour of virtual models, the force feedback and the sense of touch during the virtual interaction. This module also allows the free manipulation and collision detection of virtual objects and bone fragments using six degrees of freedom (6 DoF).

The proposed OSSys system has been implemented using the Microsoft Foundation Classes (MFC) of MS-Visual Studio 2012, the Visualization Toolkit (VTK, Kitware®) libraries for graphics rendering, and the H3DAPI libraries and axis aligned bounding boxes (AABBs) for haptic rendering and force feedback. The haptic-physics module allows the use of commercially available haptic devices such as the Omni Phantom from Sensable® or the Falcon from Novit®. In order to enable the collision detection among virtual models, the Bullet Physics libraries have also been incorporated into the system.

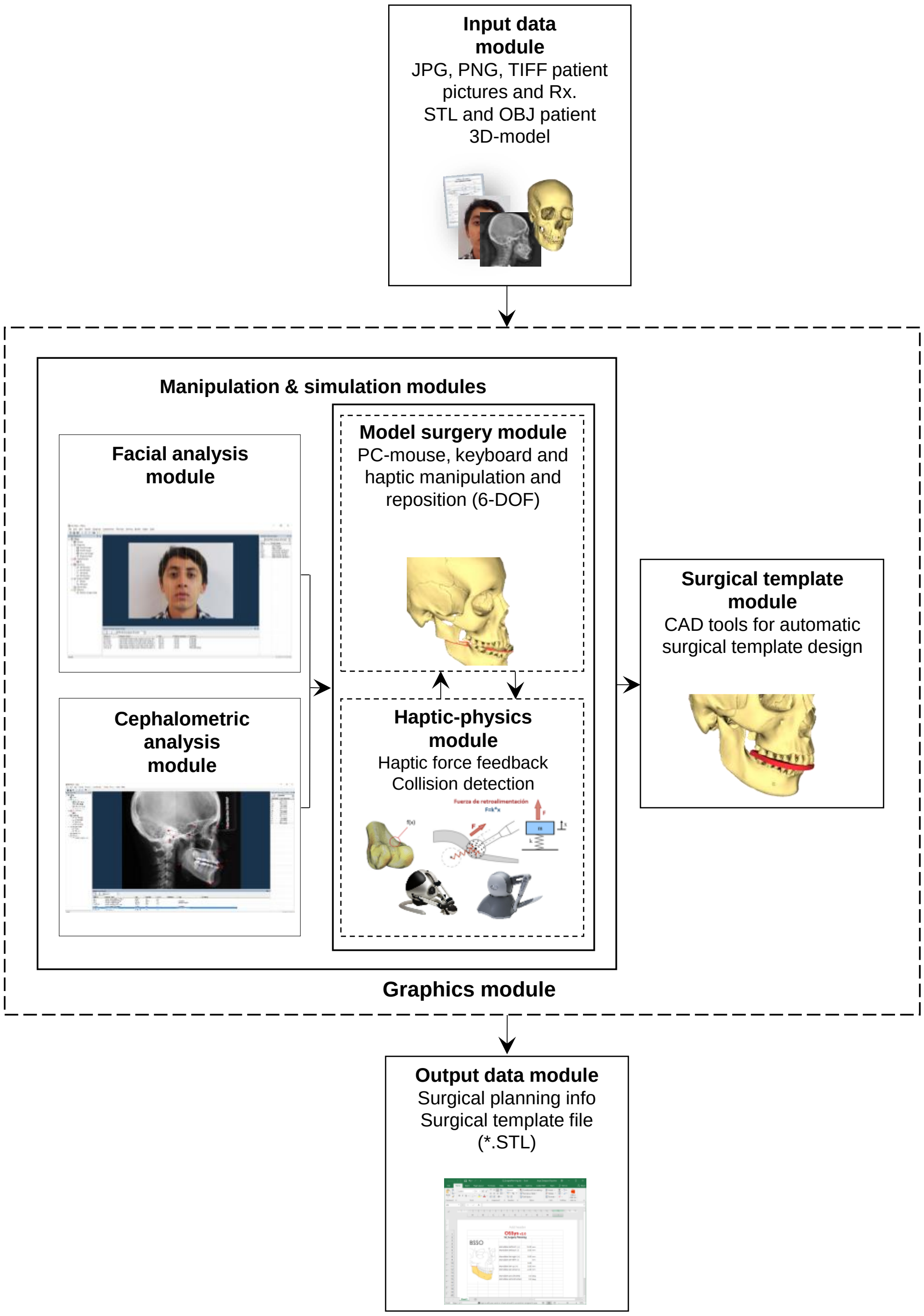


Figure 1. Architecture of the virtual haptic-enabled orthognathic surgery system.

3.1 Facial analysis module

In the traditional approach the facial analysis is carried out by the specialist on frontal and lateral patient's photographs. The facial balance and profile harmony are obtained manually by means of a standard ruler. The facial analysis comprises the sagittal third and frontal fifths facial studies used to determine the lateral and frontal facial proportions respectively, and the Powell´s study to determine the patient´s facial profile harmony. In the third facial study the distances between hairline-base of the nose, base nose-bottom nose and bottom nose-chin are compared to obtain the facial proportion (Milutinovic et al. 2014). In the fifth study the face is divided into fifths, each of those equal to the width of one eye. The Powell´s study analyses the facial soft tissue profile harmony by means of the relations between the lip and chin projections with respect to the nasal profile. The Powell´s analysis is used to determine a pre-diagnosis of the patient's malformation and suggest an orthodontics or surgical treatment.

In the clinical facial analysis module of OSSys, the sagittal third and frontal fifths facial studies, and the Powell's analysis have been implemented. These analyses are carried out on patient´s images, which can be imported into the system as standard image file formats such as bmp, jpg, jpeg, or png. The overall procedure to perform a facial analysis in OSSys is shown in Figure 2. The process starts by uploading into the system the frontal and lateral patient's photographs. Then the specialist must select the type of facial study. Next, the specialist must define the required anatomic landmarks on the patient's photography by means of the PC-mouse or haptic device. Finally, once all the landmarks have been defined, the module calculates all the facial ratios and proportions, and displays the results to the specialist. As part of the results, a clinical pre-diagnosis based on the medical literature is provided automatically to the user.

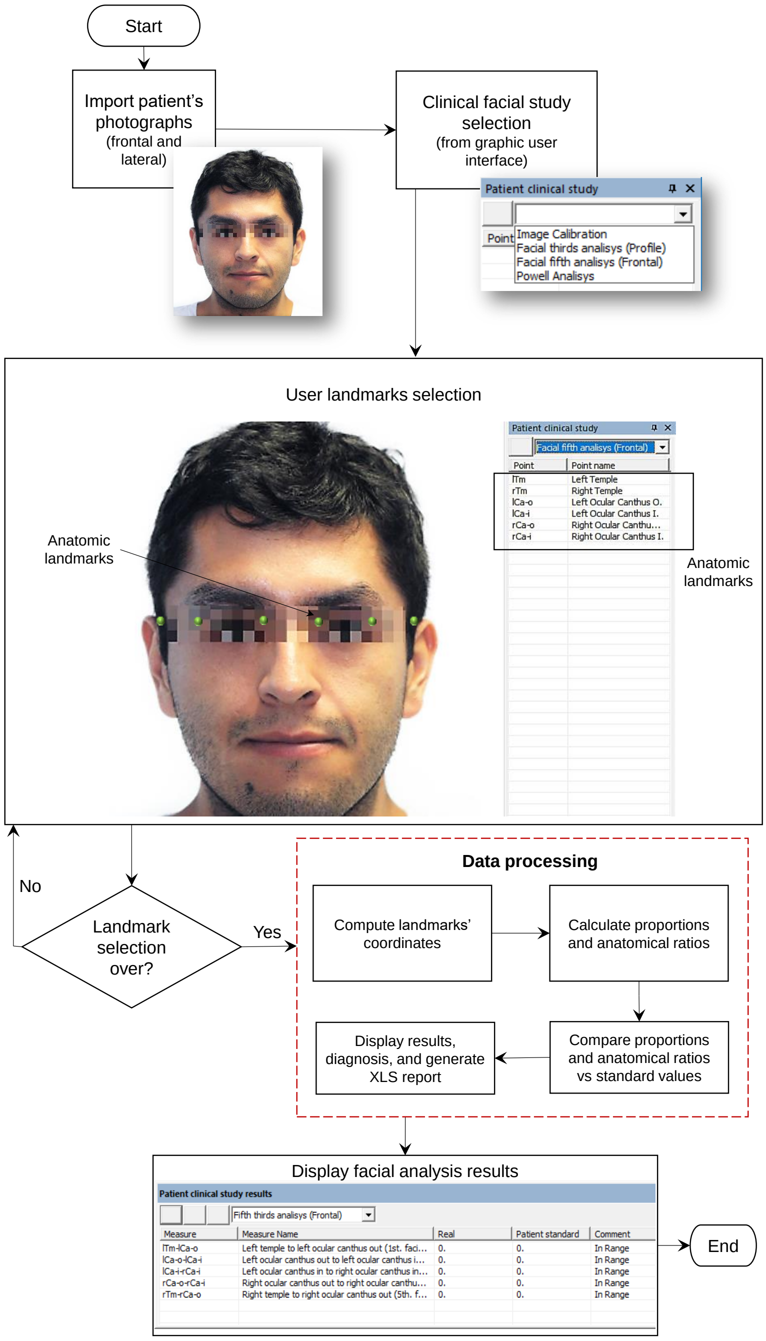


Figure 2. Overall procedure of the clinical facial analysis in OSSys.

3.2 Cephalometric analysis module

The cephalometric analysis module allows the realization of digital cephalometric analysis on a patient's sagittal radiography. The system uses the McNamara, Burstone and Legan, Steiner, Jaraback, Downs, Ricketts and Frontal, cephalometric methodologies, which are the most widely used for OGS planning. In addition, the system uses the Trujillo and Fonseca cephalometric approaches, which are commonly used to analyse Latin-American people.

The overall cephalometric analysis procedure is shown in Figure 3, which starts by importing the patient's lateral radiography as a standard image file format. Then, a calibration procedure must be performed to correct any scaling issue. The calibration is carried out by identifying two landmarks on the radiography's ruler and defining the distance between these landmarks. Next, the specialist must select the cephalometric methodologies to be used. A group of landmarks are shown for the user to identify on the radiography by means of the PC-mouse or the haptic device. Once all the landmarks have been identified, the system calculates the cephalometric values according to the selected methodologies. Finally, the results are displayed together with a cephalometric diagnosis based on the comparison between the patient's cephalometric values and the standard values provided in the medical literature. The ability to automatically provide a cephalometric diagnosis is an outstanding characteristic of the cephalometric analysis module.

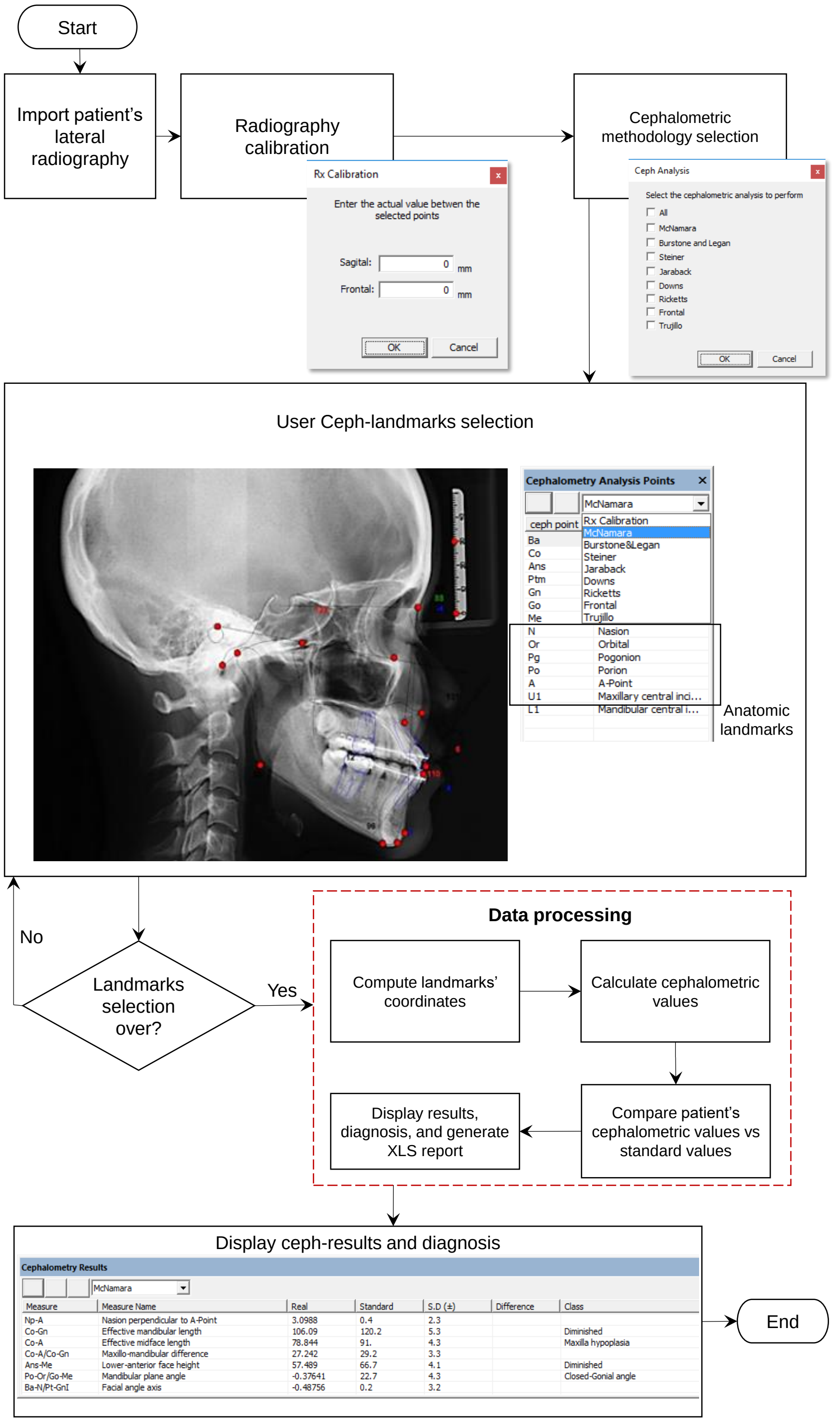


Figure 3. Virtual cephalometric analysis procedure in OSSys.

3.3 Model surgery module

In the OGS planning process, the model surgery is one of the most critical steps to achieve a successful surgical treatment and outcomes (Choi et al. 2009). At the model surgery stage the new patient's occlusion and the surgical data needed at the operating room are generated, including the surgical template; therefore, any inaccuracies or errors at this stage will affect the surgical outcomes. Conventional model surgery planning involves dental casts to be mounted on an articulator, where dental segments are identified, cut and repositioned; allowing the fabrication of intraoral wafers to guide the osteotomy segment positioning. This process relies on the accurate recording of the dental occlusion, the mounting of the casts on the articulator, the segmentation and repositioning of dental casts, and the accurate recording on the new occlusion. The complexity of this procedure may lead to many inaccuracies, which can substantially affect the post-surgery outcomes (Choi et al. 2009; Proffit et al. 2014).

In OSSys, the model surgery procedure can be carried out on digital dental models, which can be reconstructed from CT or MRI data. The overall digital model surgery procedure is shown in Figure 4, which begins by importing the patient's 3D model as an STL or OBJ file. Next, the surgeon must select one of the four different OGS procedures, LeFort I, LeFort II, BSSO and Genioplasty. According to the selected procedure, the surgeon must then identify and mark the points that will define the cutting planes on the 3D model. To mark a point, the user must locate the haptic cursor at the desired location on the 3D model and press the haptic device button. Once the model has been segmented, each bone fragment can be freely manipulated along the 6 DoF using the haptic device, the PC's mouse, or the PC's keyboard. In addition, to increase the accuracy of the repositioning movements, the system allows the user to customise the number of DoF during the manipulation process.

Once the virtual bone segments have been repositioned, the new positions are automatically computed and a repositioning report is generated. This report specifies the maxillary rotations and displacements of the maxilla and mandible models in each direction; i.e. the projection, impact, lifting, yaw, roll and pitch movements. The repositioning report is used by the surgeon to evaluate the clinical feasibility of the maxillary movement based on the patient health conditions and expected surgical outcomes.

The main characteristics of the model surgery module are the following:

- Digital dental 3D models can be imported as STL or OBJ files.
- Haptic spatial perception, shape recognition, and force feedback.
- Precise haptic bone segmentation and repositioning.
- The DoF to manipulate bone fragments can be customized.
- Real time graphics rendering of bone fragments.
- The collision detection among bone fragments can be enabled or disabled.
- Automatic generation of a repositioning report.

An outstanding feature of the model surgery module is the collision detection among the bone segments during the manipulation and repositioning tasks, which can be enabled or disabled by the user to avoid or allow, respectively, the overlapping among the bone fragments.

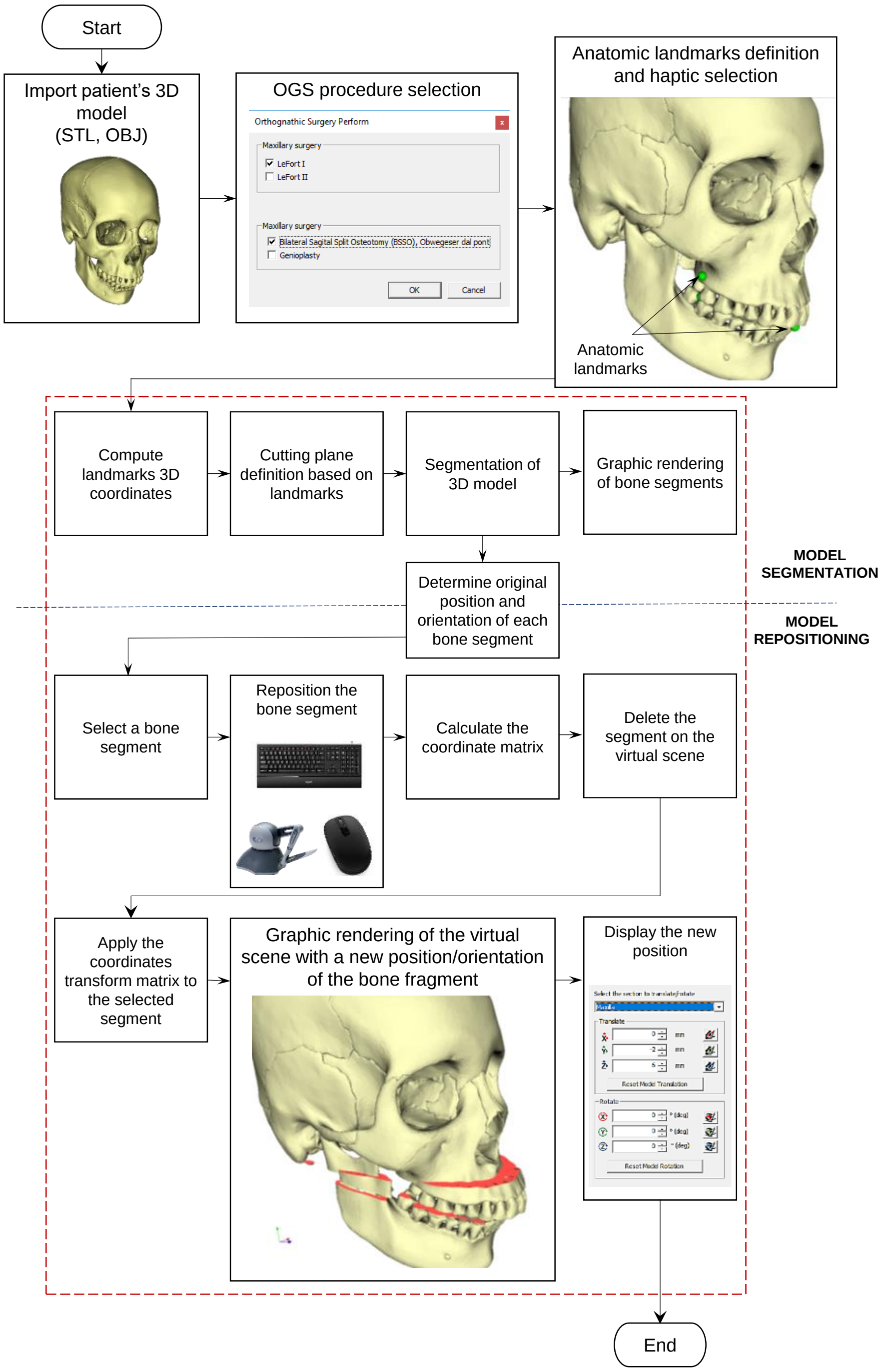


Figure 4. Virtual model surgery procedure in OSSys.

3.4 Surgical template module

The surgical template, also known as surgical wafer, is traditionally an acrylic part where the new patient's occlusion is recorded. Traditionally the wafer is fabricated manually by adapting a self-curing acrylic resin on the dental casts, previously segmented and repositioned. This traditional method for the wafer generation may also introduce inaccuracies that will affect the surgical outcomes.

In OSSys, a virtual wafer can be designed on digital dental models using the overall process shown in Figure 5. The design process starts with the calculation of the occlusal points corresponding to the desired location and orientation of the maxilla and jaw bones, previously repositioned. Next, the system automatically computes the dimensions and location of the surgical wafer based on the predefined shape shown in Figure 6. The virtual wafer is graphically rendered on the occlusal plane to verify its position and dimensions before recording the new occlusion. If needed, the surgeon can modify the location and dimensions of the virtual wafer by means of the haptic device, mouse or keyboard. Once the virtual wafer is satisfactory, the new occlusion is recorded by means of a Boolean operation. The final wafer is rendered into the virtual environment and an STL file is automatically generated, which is compatible with additive manufacturing and CAM systems.

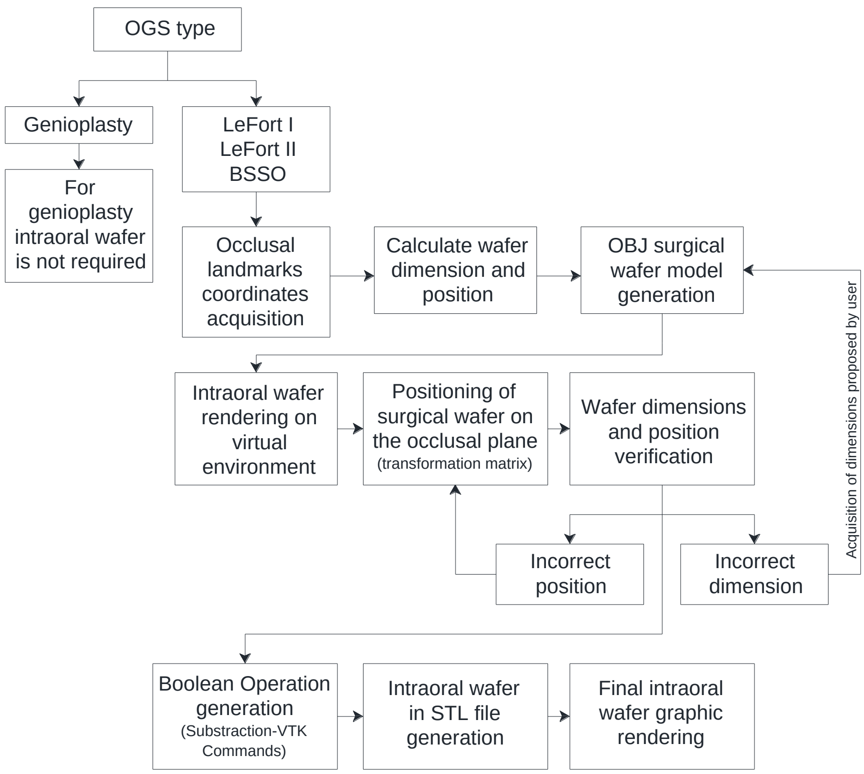


Figure 5. Overall process of surgical template generation in OSSys.

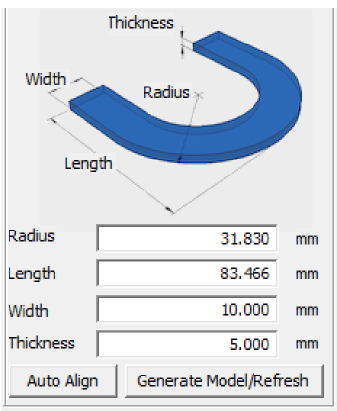


Figure 6. Virtual wafer parametric design.

The main characteristics of the surgical wafer module in OSSys are the following: 1) haptic virtual environment to create surgical wafers, 2) Computer-Aided Design of surgical wafers, 3) automatic generation of a pre-designed virtual wafer, and 4) wafer design can be exported as an STL file.

4. System evaluation

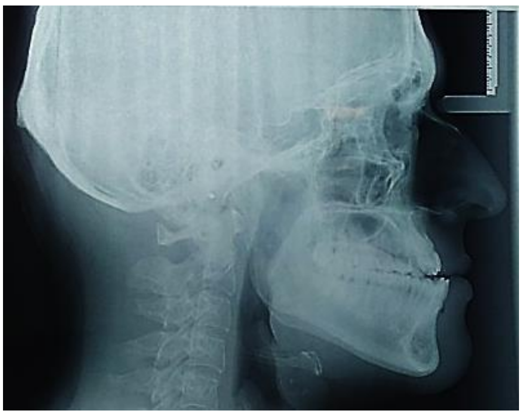
To evaluate the functionality and performance of the proposed system, a case study was selected and analysed as follows.

4.1 Case study

A case study corresponding to a 25 years old male patient with malocclusion problems requiring surgical intervention was selected. This patient was selected randomly from a group of patients seeking maxillary treatment at the Orthodontics and Maxillary Surgery postgraduate centre of Universidad Autonoma de San Luis Potosí in Mexico. Figure 7 shows the frontal and lateral photographs, radiography and 3D model of the patient.

(a)

(b)



(c)

(d)

Figure 7. Case study: (a) frontal photography, (b) lateral photography, (c) lateral radiography, (d) 3D model.

4.2 Participants

A total of 6 maxillofacial surgeons were selected to evaluate the system: 3 experts in maxillofacial surgery, aged 35-45 years, and 3 recent-graduated maxillofacial surgeons (novices), aged 27-32 years. The experts had more than 7 years of professional training and experience in orthodontics and maxillary surgery. All participants were right-handed, and none had previous experience in haptics or virtual reality systems for medical applications.

4.3 Evaluation procedure

The overall evaluation procedure is shown in Figure 8. This procedure comprised two stages: first each participant was asked to analyse the case study individually using the traditional OGS planning procedure; and then, one week later after completing the traditional planning, each participant was asked to analyse the case study individually using the virtual approach. Each participant went through a period of training, which included an introduction to the system and a familiarization practice on the use of the haptic device and the system. During the training period, five surgery planning trials were executed by each participant using generic models and lateral radiographies. After the training period, each participant received the patient's lateral radiography and the 3D model, previously reconstructed from CT images. For the traditional planning approach, each participant acquired individually the dental casts and photographs of the patient. At each stage of the two planning processes, the task completion time (TCT) was measured.

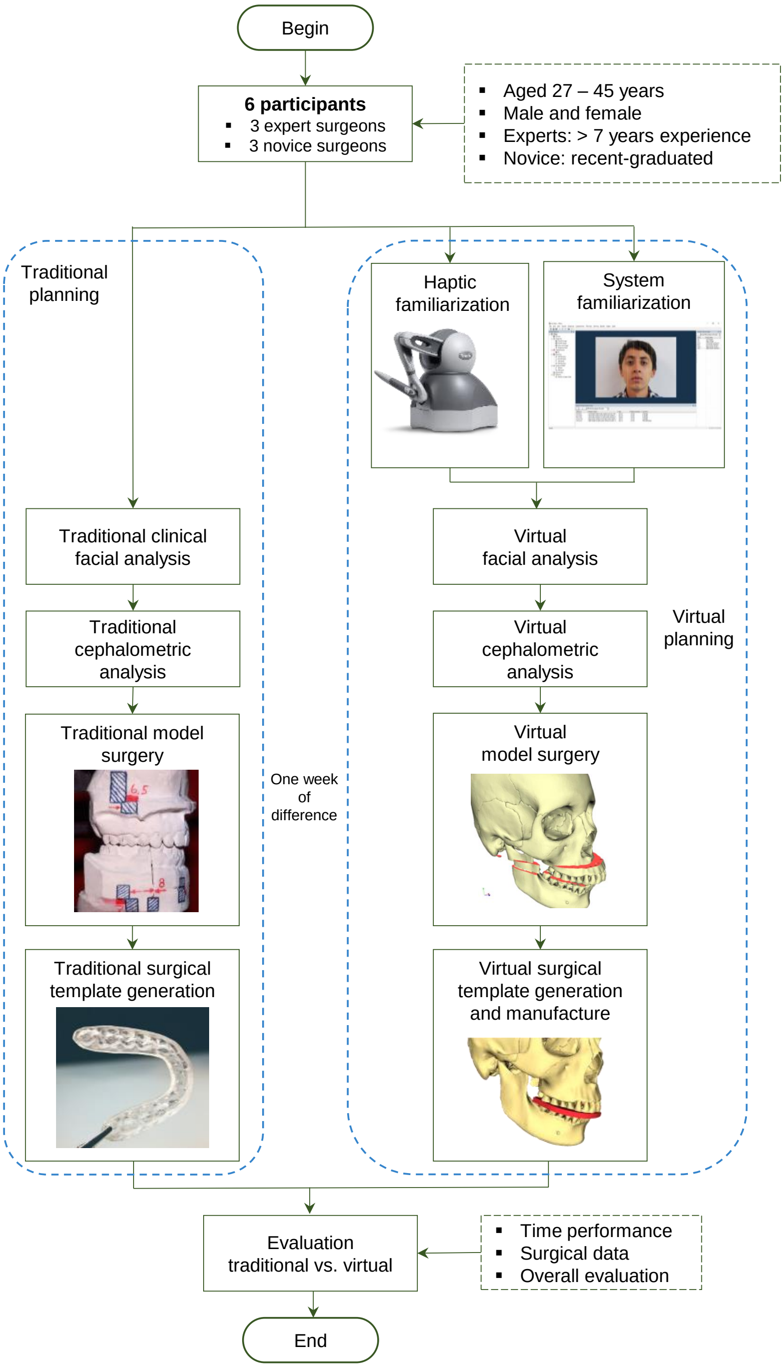


Figure 8. Overall evaluation methodology.

5. Results and discussion

5.1 Facial analysis

The results of the facial analysis obtained from the traditional and the virtual planning approaches are presented in Table 2. These results evidence that the diagnosis using both approaches is very similar, a surgical treatment is required. However, in terms of performance, the virtual approach led to a significant reduction of up to 88% in the TCT. This time reduction is because in the virtual approach the manual measuring process of the facial metrics is eliminated. Regarding the time performance of the experts and novices, the results reveals that in the traditional approach the expert's TCT is 23 minutes smaller than the novices' TCT; however, in the virtual approach this difference is reduced to only 2.3 minutes.

Table 2. Clinical facial analysis results by the traditional and virtual methods.

	Novice surgeons		**Expert surgeons**	
	Traditional	**Virtual**	**Traditional**	**Virtual**
Third facial analysis	Second facial third diminished	Second facial third diminished	Second facial third diminished	Second facial third diminished
Fifth facial analysis	Third facial fifth diminished	Third facial fifth diminished	Third facial fifth diminished	Third facial fifth diminished
Powell's analysis	Surgical and orthodontic treatment	Surgical treatment	Surgical and orthodontic treatment	Surgical treatment
Average TCT in minutes (SD)	45 (5.24)	5.5 (2.07)	22 (4.73)	3.2 (1.04)

SD: standard deviation

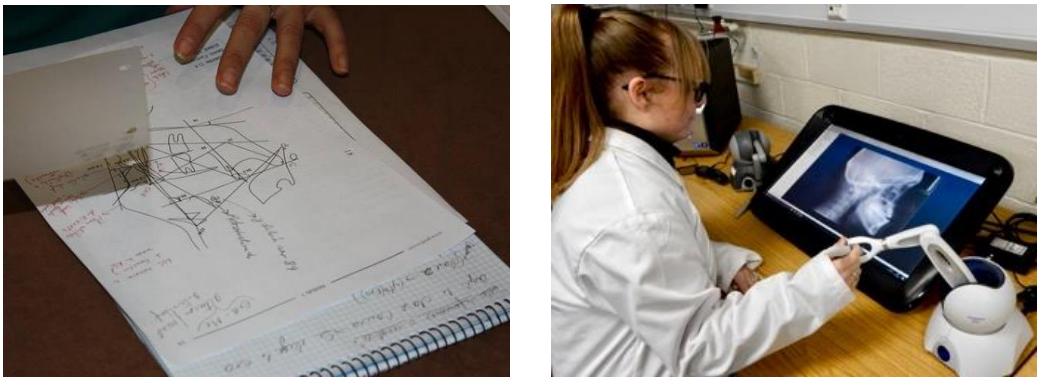
5.2 Cephalometric analysis

The cephalometric analysis was carried out using the Ricketts methodology. Figure 9 shows a participant performing the traditional cephalometric analysis and a participant carrying out the virtual cephalometric analysis. The cephalometric results are summarized in Table 3. According to this table, the cephalometric values obtained using both approaches have led to the same diagnosis and treatment; i.e. the patient requires a LeFort I Bilateral sagittal split osteotomy (BSSO) surgical procedure. The clinical diagnosis proposed by the virtual system agrees with the diagnosis made by the experienced surgeons using the traditional approach. However, the virtual cephalometric analysis in OSSys was made only in a small fraction of the TCT required in the traditional approach (6.4% for the novices and 19% for the experts). It is also evident that the TCT of the novices when using the traditional approach, is more than twice the corresponding time required by the experts; however, this difference is eliminated in the virtual approach.

Table 3. Cephalometric results using the traditional and virtual methods.

	Novice surgeons		Expert surgeons	
	Traditional	**Virtual**	**Traditional**	**Virtual**
Facial profile	Concave	Concave	Concave	Concave
Overbite in mm (SD)	-3 (1)	-3.24 (0.5)	-3 (0.7)	-3.62 (0.4)
Molar ratio	Class III	Class III	Class III	Class III
Diagnosis and proposed treatment	Bimaxilar (LeFort I BSSO)	LeFort I BSSO	Bimaxilar (LeFort I BSSO)	LeFort BSSO
Average TCT in minutes (SD)	117 (5.2)	7.5 (1.26)	43 (4.02)	8.2 (3.37)

SD: standard deviation, BSSO: Bilateral sagittal split osteotomy.



(a) (b)

Figure 9. Cephalometric analysis: a) traditional method, b) virtual method.

5.3 Model surgery

In the traditional model surgery procedure, each surgeon was asked to get the patient's dental cast models and mount them on an articulator, as shown in Figure 10. Reference lines were then indicated on each model before cutting and relocate each maxilla. On the other hand, the virtual model surgery was carried out on the patient’s digital models in OSSys. The haptic device was used by the surgeons to feel and mark on the virtual model the anatomical points that define the cutting planes. The repositioning of the models was also carried out using the haptic device. Figure 11 shows the segmented digital dental models.

Figure 10. Patient's dental casts mounted on an articulator.

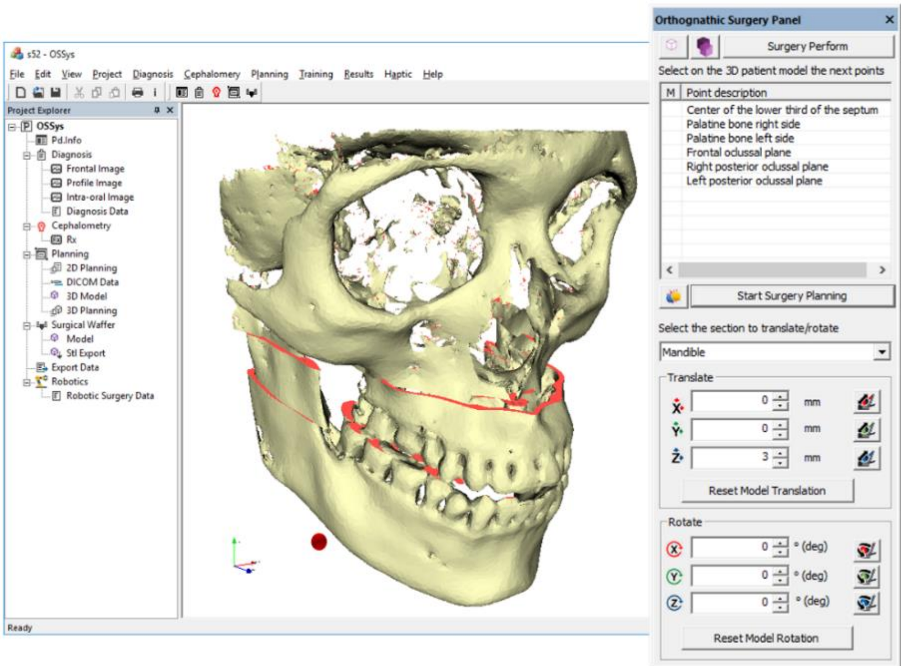


Figure 11. Segmented and repositioned digital dental model.

The results of the model surgery by the traditional and virtual methods are summarized in Table 4. These results show that the bone displacements predicted by both methods are very similar: however, the performance of the virtual approach is superior than the traditional approach because it only requires a small fraction of the time to complete the traditional model surgery (5.8% for novice surgeons and 7.6% for experienced surgeons).

This superior performance is because in the digital model surgery approach the dental casts fabrication, mounting on an articulator, marking of reference lines, and measuring activities are eliminated. Moreover, the errors associated to these activities are also avoided.

Table 4. Model surgery results using the traditional and virtual methods.

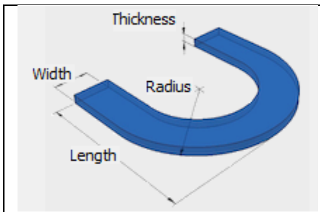
	Novice surgeons		Expert surgeons	
	Traditional	**Virtual**	**Traditional**	**Virtual**
Surgery type	LeFort I BSSO	LeFort I BSSO	LeFort I BSSO	LeFort I BSSO
Maxillary projection in mm (SD)	9.1 (0.7)	10.3 (0.65)	9.5 (0.4)	10.42 (0.21)
Jaw projection in mm (SD)	2.3 (0.6)	3.1 (0.48)	2.7 (0.5)	3.03 (0.35)
Average TCT in minutes (SD)	263 (20.51)	15.2 (3.1)	127 (10.2)	9.7 (2.93)

SD: Standard deviation, BSSO: Bilateral sagittal split osteotomy.

5.4 Surgical template

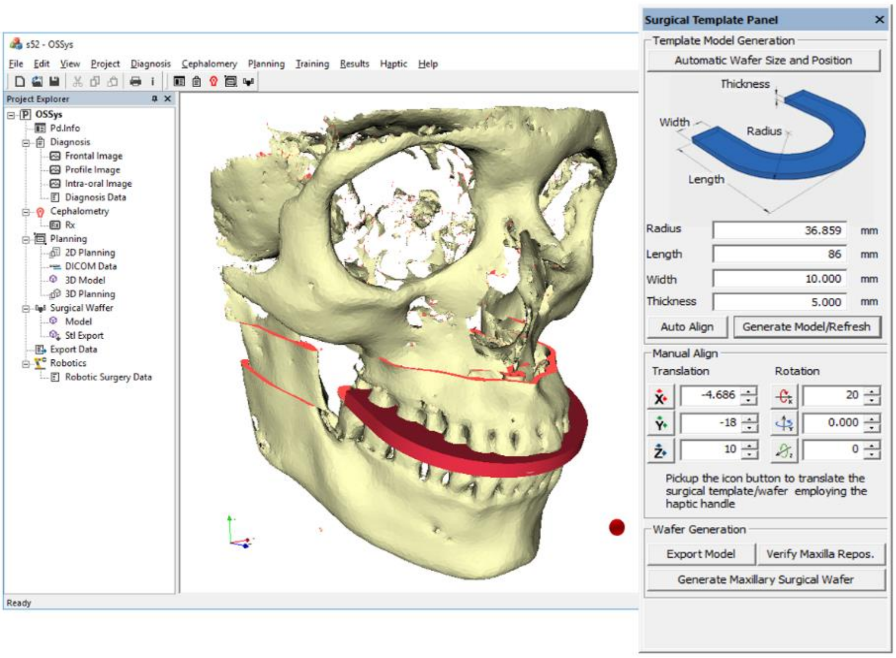
The generation of the surgical template by the traditional and virtual methods was carried out from the previously repositioned dental casts and digital models, respectively. The design parameters and the average time to generate the surgical template are shown in Table 5. The time to generate the surgical template in the virtual approach comprises the time to design the template and the time to fabricate the template in an AM Creator Pro system from FlashForge© using PLA material. The digital and the physical wafers are shown in Figure 12.

Table 5. Design parameters and times to create the surgical template.

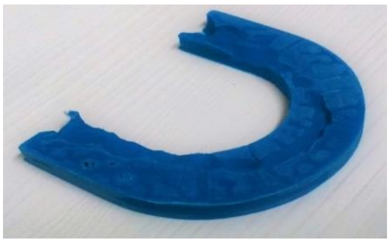
	Novice surgeons		Expert surgeons	
	Traditional	**Virtual**	**Traditional**	**Virtual**
Thickness in mm	-	3.0	-	3.0
Radius in mm (SD)	-	32 (2.3)	-	31 (1.5)
Length in mm (SD)	-	57 (3.01)	-	59 (1.24)
Width in mm (SD)	-	17 (1.2)	-	15 (0.81)

Creation time in minutes (SD)	70 (5.2)	-	43 (4.02)	-
Average time to design the template in minutes (S.D)	-	7.5 (1.26)	-	8.2 (3.37)
Fabrication time by additive manufacture in minutes	-	45	-	45

SD: Standard deviation.



(a)



(b)

Figure 12. Surgical template generation: a) virtual wafer design, b) physical wafer fabricated by additive manufacturing.

In the case of the novice surgeons, the time to generate the wafer using the traditional approach is much larger than the corresponding time needed when using the virtual approach. On the other hand, in the case of the experienced surgeons, the time to generate the wafer using the traditional approach is smaller than the corresponding time when using the virtual approach. However, the design of the virtual wafer in OSSys is relatively fast; it takes about 8 min to complete the design, which is a small fraction of the time to create the wafer using the traditional approach. In addition, although the time to fabricate the wafer in an AM system is relatively high (45 min), it corresponds to machine processing time and no to the specialist's time, as in the traditional approach.

5.5 Time performance

Table 6 summarizes the TCTs for each planning task corresponding to the traditional and the virtual approaches. In general, the results show that the proposed virtual OGS planning approach leads to a significant reduction of the time required to plan an orthognathic surgery (about 90% reduction), and without compromising the diagnosis and quality of the planning outcomes. This time reduction confirm that the use of the proposed integrated virtual approach is feasible, improving the performance of the traditional OGS planning process. Moreover, the performance difference between an experienced surgeon and a novice surgeon in the traditional planning process, is shortened in the virtual planning approach.

Table 6. Task completion times corresponding to the traditional and virtual OGS planning processes.

Surgical planning stage	**Task completion time (min) (SD)**			
	Novice surgeons		**Expert surgeons**	
	Traditional	**Virtual**	**Traditional**	**Virtual**
Clinical facial study	45 (5.24)	5.5 (2.07)	22 (4.73)	3.2 (1.04)
Cephalometric analysis	117 (10.37)	10.2 (3.06)	75.2 (7.19)	5.2 (2.34)
Model surgery	263 (20.51)	15.2 (3.1)	127 (10.2)	9.7 (2.93)
Surgical template generation	70 (5.2)	7.5 (1.26)	43 (4.02)	8.2 (3.37)
Total	**495 (10.33)**	**38.4 (2.37)**	**267 (6.53)**	**26.3 (2.42)**

SD: Standard deviation

5.6 Overall evaluation

In general, it can be said that the functionality of the proposed haptic-enabled virtual reality system for integrated OGS planning has been demonstrated. The proposed system integrates all the stages of the OGS planning process into a unified virtual platform. The system is able to assist surgeons from the clinical facial analysis to the generation of the surgical template, producing the reliable surgical data required at the operating room. Moreover, the overall performance of the planning process is improved by reducing the time required to complete each task of the OGS planning process but without reducing the quality of the results. Additionally, many of the potential errors related to the traditional approach activities such as measuring facial and cephalometric values, creation of dental casts, mounting of casts on the articulator, segmentation and repositioning of dental casts, and wafer generation, are eliminated in the proposed virtual method.

The main advantages of the proposed integrated virtual OGS planning system are:

- Automatic calculation of facial and cephalometric values.
- Automatic generation of facial and cephalometric pre-diagnoses.
- Haptic-enabled interaction and manipulation of 3D models.
- Haptic-enabled virtual environment to perform model surgeries on digital models.
- Haptic-enabled Computer-Aided Design of surgical templates.
- Automatic generation of surgical data.

The introduction of haptics into the complete OGS virtual planning process has increased the practicality and intuitiveness of the system; users are able to freely navigate and feel anatomic features to define landmarks, segment dental models and manipulate bone fragments in a more realistic way. In addition, the incorporation of diagnostic tools into the OSSys system have also allowed the automatic generation of computerized pre-diagnoses to support surgeons and reduce potential diagnostic errors. However, it is important to mention that the pre-diagnoses generated by the system need to be validated by the surgeons. To the best knowledge of the authors, none of the currents systems reported in the literature can provide computerized diagnoses for OGS planning. On the other hand, the integration of CAD tools into the system has allowed the rapid design of surgical templates without requiring any previous CAD experience. The surgical wafer can be designed by the surgeons in about 8 minutes. Finally it can be mentioned that all participants were glad with the usability and performance of the system, suggesting its practical use in the academy and hospitals.

6. Conclusions

A novel haptic-enabled virtual reality system for total orthognathic surgery planning has been presented. The proposed system integrates the four main stages of the traditional OGS planning process: clinical facial analysis, cephalometric analysis, model surgery, and surgical template generation. By incorporating haptics and CAD tools, the system can assist surgeons along the complete planning process. A case study was analysed, and the results have demonstrated the functionality and efficiency of the proposed virtual planning approach, which is far superior to the traditional planning method.

Future work considers the accuracy evaluation of the virtual OGS planning system, including post-operative outcomes and a statistical analysis of the results and errors. The integration of soft tissue post-operative predictions and navigation tools are also part of the future work.

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Conflict of interest

The authors declare that they have no conflict of interest.

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